Production of various species of focused ion beam

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The ability to generate various ion species makes the multicusp plasma ion source an excellent candidate for maskless resistless lithography application. In this article, the mass spectra of both positive and negative ions for phosphorus, BF_3, and oxygen multicusp plasmas are presented. It is shown that over 90% P^+ ions are produced. The production of BF_2^+ and O_2^+ increases with increasing gas pressure, and decreases with increasing source power. With optimization of source operating parameters, approximately 85% BF_2^+ and over 90% O_2^+ have been achieved. [DOI: 10.1063/1.1427351]

I. INTRODUCTION

Focused ion beams (FIBs) have been used extensively in the semiconductor industry for applications such as micromachining, mask repair, circuit modification, and failure analysis.[1] As the lateral dimensions of semiconductor devices are scaled down, next generation lithography (NGL) technology will replace optical lithography in integrated-circuit manufacture. Among four major alternative NGL approaches, ion beam lithography is the only one which can provide both maskless and resistless patterning. As such, it can potentially make nano-fabrication much simpler. For this to happen, the ion source must be able to produce a variety of ion species. In a conventional FIB system, a liquid–metal ion source is used, limiting the species to certain metallic elements such as gallium.

Plasma sources, in particular multicusp generators, have been used for many applications, such as in neutral beam injectors for fusion devices, particle accelerators, ion implantation systems, neutron tubes for oil well logging and proton therapy machines.[2,3] One of the advantages of using multicusp plasma source is that it can generate different ion species, such as ions of noble gases, phosphorus, boron, oxygen, etc. A multicusp source can produce uniform plasma over a large area,[2] therefore a single source can be used to generate a large number of closely packed beamlets for parallel processing—an advantage which cannot be found in any other type of ion source. Direct doping of a Si wafer with a focused P^+ or BF_2^+ beam eliminates the necessity of resist, which is conventionally used as a mask for ion implantation. Thin oxide formed by selectively oxidizing the poly-Si surface with a focused O_2^+ beam can be used as a hard mask for gate patterning in complementary metal–oxide–semiconductor device process. Neither a stencil mask nor resist material is needed in such a lithography process.

Negative ions have been used in ion implantation and modification of materials. The negative charge results in reduced surface charging voltage of insulated substrate because the incoming negative charge of the ions is easily balanced with the outgoing negative charge resulting from secondary electron emission.[4]

In this article, production of both positive and negative ions using a multicusp ion source will be discussed for phosphorus, BF_3, and oxygen plasmas. Optimization of source operating parameters to achieve maximum purity ion species production will also be discussed.

II. MULTICUSP PLASMA SOURCE

The new FIB system that is being developed at Lawrence Berkeley National Laboratory employs a multicusp plasma generator.[5,6] Figure 1 shows a schematic diagram of the multicusp ion source. The multicusp source can be operated easily with a dc filament or radio frequency (rf) coil induction discharge with gaseous or metallic elements. In this particular case, a rf antenna is used rather than a hairpin tungsten filament cathode to provide clean plasmas and long-life, reliable operation. It has been shown that the axial ion energy spread of the multicusp source can be reduced from 6 eV to below 1 eV by using a permanent magnetic filter.[7]

The constituents of the plasma are ions and electrons, as well as un-ionized neutrals. In general, most discharges contain not only positive ions, but also negative ions. By changing the polarity of the extraction system, either positive or negative ion beams can be extracted. Negative ion implantation or deposition reduces surface charging of the insulated substrate, because the outgoing secondary electrons balance the incoming negative charge of the ions.[4] In FIB lithography application, the critical dimension is less deteriorated by the deflection of charged substrate, and an external source of electrons for charge neutralization is not needed.

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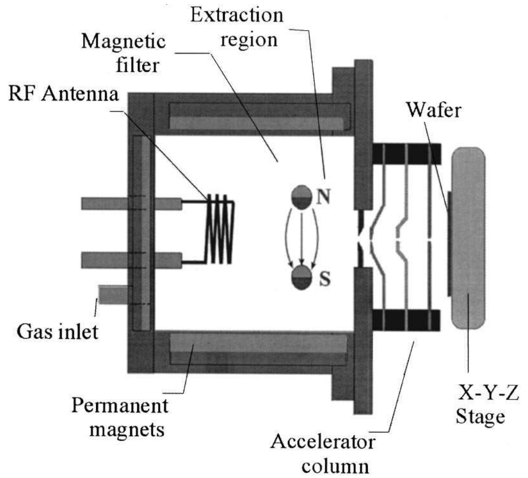

FIG. 1. Schematic diagram of a rf discharge multicusp source. A pair of permanent magnets is used to lower the axial energy spread.

III. PRODUCTION OF VARIABLE ION SPECIES

A. P_x^+ and P_x^- ions (x=1,2,3,4,5)

To generate phosphorus plasma, solid phase phosphorus is used. A small oven is attached to the gas inlet on the source back plate. The oven is heated up to around 425 °C to vaporize the sample. Phosphorus vapor is introduced into the multicusp source to generate phosphorus plasma.

Figure 2 shows the mass spectra of phosphorus plasma, for both positive and negative ions. Figure 2(a) shows that over 90% of the positive ion species are P^+, less than 7% are P_2^+, and less than 1% are P_3^+ and P_4^+. On the mass spectrum, the peak of Ar^+ is due to the residual argon gas in the source. Argon is used as a start-up gas to warm up the source wall before phosphorus vapor is introduced into the source chamber. The hot source wall helps to reduce phosphorus condensation. After a stable phosphorus plasma is achieved, the argon gas supply can be shut off. Eventually all argon gas in the source chamber should be pumped away. As shown in Fig. 2(b), more negative cluster phosphorus ions such as P_2^-, P_3^-, etc., are produced than positive ones.

B. BF_x^+ and BF_x^- ions (x=1,2,3,4,5)

Figure 3 shows the mass spectra of BF_3 plasma for both positive and negative ions. For positive ions in Fig. 3(a), B^+, BF^+, BF_2^+ ions are the major ion species. Compared to BF^+ and BF_2^+, B^+ is negligible. For negative ions, higher fluorine content cluster ions are observed. This is probably due to the higher electron affinity with the presence of F. However, BF_2^- was not found in the spectrum.

Focused boron ions can be selectively implanted into the Si substrate to form ultrashallow junctions. The maximum production of a single ion species is very important to control critical dimension and the junction depth profile. Figure 4 shows the relationship between BF_2^+ ion percentage and source power and BF_3 gas pressure. The BF_2^+ percentage was measured from different mass spectra at various rf power and BF_3 gas pressure. At 1 kW rf power, BF_2^+ ion percentage increases from 25% at 5 mTorr to almost 70% at 25 mTorr. At 6 mTorr of BF_3 gas pressure, BF_2^+ ion percentage de-

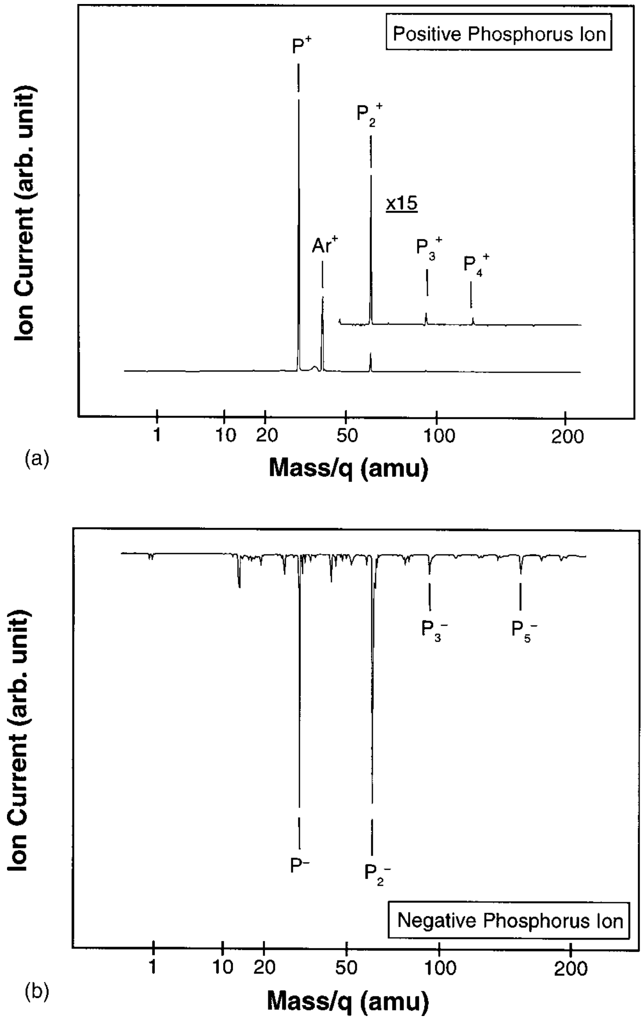

FIG. 2. Mass spectra of phosphorus plasma: (a) positive ions; (b) negative ions.

creases from 50% at 900 W to around 25% at 1500 W. By optimizing the gas pressure and source power, over 85% of BF_2^+ ions can be achieved at 25 mTorr and 900 W conditions.

C. O_x^+ and O_x^- ions (x=1,2)

Figure 5 shows the mass spectra of oxygen plasma for both positive and negative ions. For the positive ions, two ion species are produced: O^+ and O_2^+. Adjusting the source operation condition, which is similar to that for BF_2^+ production, can optimize the percentage of O_2^+ ions. By increasing the oxygen gas pressure, decreasing the rf power, and decreasing the gap between rf quartz antenna and extraction aperture, the percentage of O_2^+ increases. Over 90% of O_2^+ can be achieved. For the negative oxygen ions as shown in Fig 5(b), much more O^- ions are produced than O_2^- ions.

IV. SUMMARY

For maskless and resistless patterning using ion beams, the ion source must be able to produce a variety of ion species. The multicusp plasma ion source has been used to provide phosphorus, boron, and oxygen ions for direct ion implantation and deposition applications. The mass spectra of

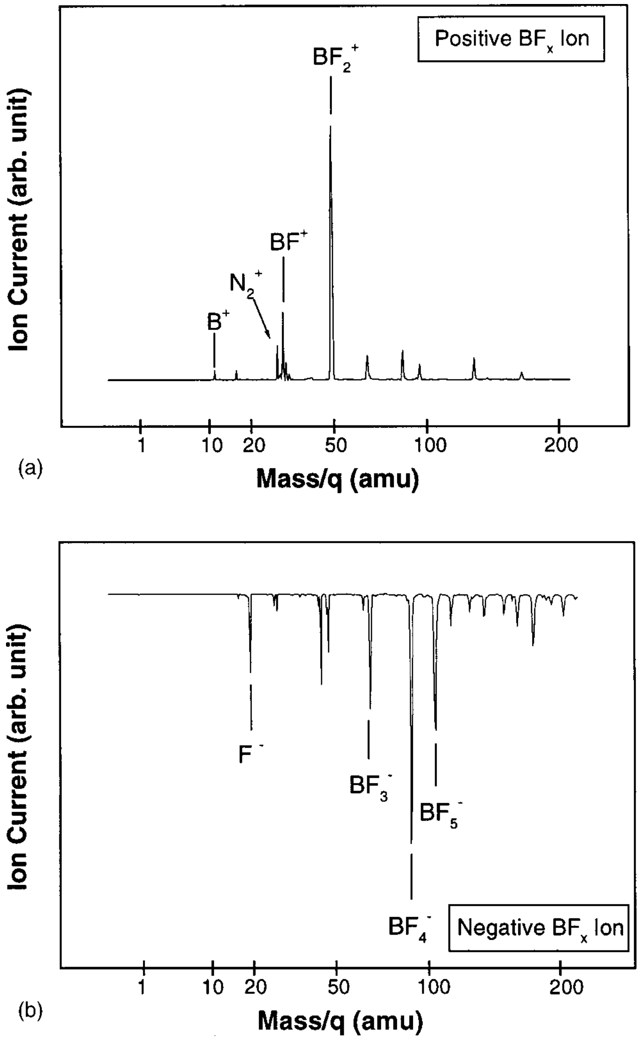

FIG. 3. Mass spectra of BF_3 plasma: (a) positive ions; (b) negative ions.

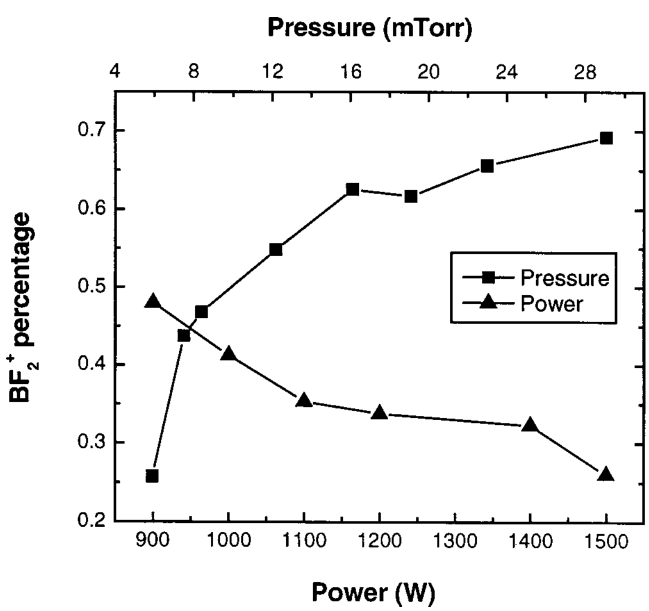

FIG. 4. Relationship between BF_2^+ percentage in a BF_3 plasma and gas pressure, rf power.

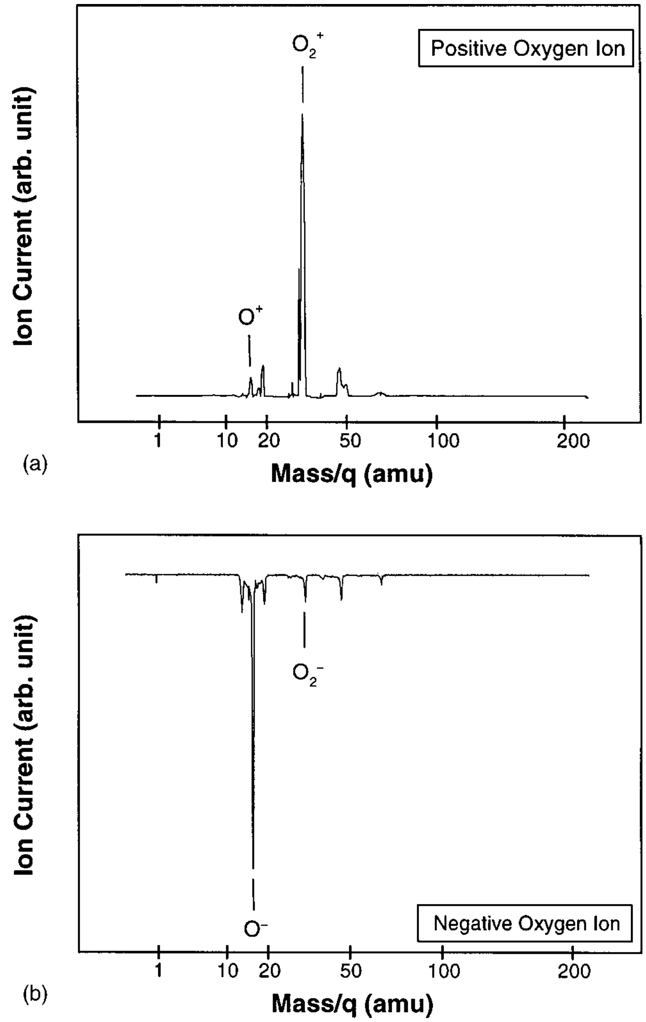

FIG. 5. Mass spectra of oxygen plasma: (a) positive ions; (b) negative ions.

both positive and negative ions have been measured for phosphorus, BF_3, and oxygen multicusp plasmas. More varieties of negative ions were observed in both the phosphorus plasma and BF_3 plasmas. Over 90% of P^+ ions have been achieved. Increasing the gas pressure and decreasing the source power can maximize the production of BF_2^+ and O_2^+. With optimization of source operation parameters, around 85% of BF_2^+ and over 90% of O_2^+ have been achieved.

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